6

PHOTONICS

Introduction

Laser is the acronym for Light Amplification by stimulated Emission of Radiation.

Laser is one of the outstanding invention of the second half of the last century. Laser is a light source but it is very much different from many of traditional light sources. Laser is a photonic device to produce intense, monochromatic, coherent and unidirectional beam of light. Lasers are in fact generators of light. They are based on the amplification of light by means of stimulated emission of radiation of atoms or molecules. In 1917 Einstein predicted the possibility of such stimulated radiation.

In 1952 Townes, Gordon and Zeiger in U.S.A. and Basov and Prokhorov in USSR independently suggested the principle of generating and amplifying microwave oscillations based on the concept of stimulated radiation. It lead to the invention of MASER (Microwave Amplification of by Stimulated Emission of Radiation) in 1954. In 1958 Townes and Schawlow and Basov and Prokhorov independently expressed their ideas about extending the maser concept to optical frequencies which lead to the invention of laser. Townes, Basov and Prokhorov both received Nobel prizes for their work in this field. In 1960 Theodore Maiman of Hughes Research Laboratories (HRL) fabricated the first laser using a ruby crystal as the amplifier and a flash lamp as the energy source. After this a series of lasers were discovered.

It is due to the characteristics of lasers such as extreme brightness (intensity), monochromaticity, high directionality and coherence, they have wide applications in different areas. The laser is used in metal working such as welding and piercing holes in metals. Lasers are used as saw to cut thick metal sheets, as a phonograph needle for compact discs, as a knife during surgical operations (bloodless surgery). They are used in optical communications, weapon guidance in wars, detecting and ranging objects at greater distance; in holography and in a wide variety of other fields. The discovery of laser and its technological applications gave birth to a new field namely photonics.

Quantum behaviour of light (preliminary ideas)

In 1900, Max Planck proposed that light consists of discrete bundles of energy.

The amount of energy of each bundle is $h\upsilon$. These bundles of radiant energy are called quanta. In 1905 Einstein refined the quantum hypothesis of Planck by introducing photon concept. A photon represents the minimum energy unit of light. Each photon carries an amount of energy proportional to the frequency of the light wave, as given by

$$E = h\upsilon$$

where h is Planck's constant. It is obivious that the higher the frequency of a photon, the more the energy it possesses. Thus UV light photons are more energetic than visible light photons. The light energy E emitted by a source must be an integral multiples of the photon energy. Thus

$$E = nh\upsilon \text{, where } n = 1, 2, 3 \ldots\ldots$$

Absorption and emission of light

In an atom, an electron in the ground state is stable and moves continuously in that orbit without radiating energy. When the electron receives an amount of energy equal to the difference of energy of the ground state and one of the excited states, it absorbs energy and jumps to the excited state. There are variety of ways in which the energy may be supplied to the electron. One way is to illuminate the material with light of appropriate frequency $\upsilon = \frac{E_2 - E_1}{h}$. The photons of energy $h\upsilon = E_2 - E_1$ induce electron transition from the energy level E_1 to the level E_2 as shown in figure.

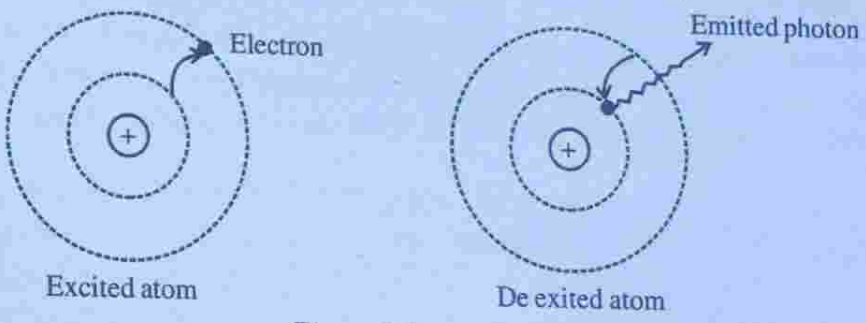

Figure 6.1

However, the electron cannot stay in the excited state for a longer time. The coulomb attraction due to the positive nucleus pulls the electron back to the initial inner orbit and the electron returns to the ground state. The excited electron has excess energy equal to $E_2 - E_1$ and it has to get rid of this energy in order to come to the lower energy level. The only mechanism through which the electron can lose its excess energy is through the emission of a photon. Therefore, the excited electron emits a photon of energy $h\upsilon = E_2 - E_1$ and returns to the ground state.

When we see light from any source we actually see electrons jumping from excited states to lower states. This type of emission of light which occurs on its own is known as spontaneous emission and is responsible for the light coming from candles, electric bulbs, fire, stars, sun etc. conventional sources of light.

Population

The atoms of each chemical element have their own characteristic system of energy levels. The energy difference between the successive energy levels of an atom is of the order of 1eV to 5eV. The energy levels are common to all the atoms in a system which is composed of identical atoms. We can therefore say that a certain number of atoms occupy a given energy state. The number of atoms per unit volume that occupy a given energy state is called the population of that energy state. The population N of an energy level E depends on the temperature and is given by

$$N = e^{-\frac{E}{kT}} \qquad \ldots\ldots (1)$$

where k is known as Boltzmann's constant.

This is called Boltzmann's equation.

In a material, atoms are distributed differently in different energy states. The atoms normally tend to be at their lowest possible energy level which need not be the ground state. At temperatures above OK, the atoms always have some thermal energy and therefore, they are distributed among the available energy levels according to their energy.

At thermal equilibrium, the number of atoms at each energy level decreases with increase of energy level. If we consider two energy levels E_1 and E_2 their populations can be computed with the help of Boltzmann's equation. Thus

$$N_1 = e^{-\frac{E_1}{kT}}$$

and $$N_2 = e^{-\frac{E_2}{kT}}$$

$$\therefore \quad \frac{N_2}{N_1} = e^{-\frac{(E_2 - E_1)}{kT}} \qquad \ldots\ldots (2)$$

$\frac{N_2}{N_1}$ is called relative population.

As an example let us calculate the atomic population of hydrogen gas at room temperature at 300K at the first excited level.

Here $E_1 = -13.6eV$, $E_2 = -3.39eV$

and $T = 300K$.

$$E_2 - E_1 = -3.39 - -13.6 = 10.21eV$$

$$kT = 8.6\times10^{-5}\frac{eV}{K}\cdot 300K = 0.025eV$$

$$\therefore \quad \frac{N_2}{N_1} = e^{\frac{10.21}{0.025}} = e^{-408.4} \approx 0$$

It shows that at room temperature all atoms are in the ground state. If temperature is raised to 6000 K

$$\frac{N_2}{N_1} = e^{\frac{10.21}{0.516}} = e^{-19.79} = 2.5\times10^{-9}$$

It shows that in a material at thermal equilibrium more atoms are in the lower energy state. We call such a distribution of atoms as normal distribution.

Einsteins prediction of stimulated emission

Einstein predicted in 1917 there must be a second emission process to establish thermodynamic equilibrium. For example if we illuminate a material with light of suitable frequency the atoms in it absorb light and go to higher energy states. The excited atoms tend to return randomly to the lower energy state. As the ground state population is very large, more and more atoms are excited under the action of incident light and it is likely that a stage may be reached where all atoms are existed. This violates thermal equilibrium condition. Therefore, Einstein suggested that there could be additional emission mechanism by which the excited atoms can make downward transitions. He predicted that the photons in the light field induce the excited atoms to fall to lower energy states and give up their excess energy in the form of photons. He called this second type of emission as stimulated emission.

Interaction of light with matter

According to classical physics the process of transfer of energy from atom to light is not possible. But this is possible from the point of view of quantum mechanics. The transfer of energy from atom to light results in the light amplification. A light amplifier can be further converted into a source of light having superior characteristics compared to traditional light sources. This superior characteristic light source formed due to the transfer of energy from atom to light which is amplified is

termed as laser. In order to understand the development of laser we have go for the quantum mechanical treatment.

We know that the radiation incident on a material is a stream of photons according to quantum theory and each photon carries an energy $E = h\upsilon$. We assume that two energy levels of the atoms in the material have an energy difference, $E_2 - E_1 = h\upsilon$. When photons travels through material medium three different process are likely to occur. They are absorption, spontaneous emission and stimulated emission. We study these in detail.

Absorption

Induced absorption

Suppose an atom is in the lower energy level E_1. If a photon of energy $h\upsilon = E_2 - E_1$, is incident on the atom, photons gives its energy to the atom and disappears. Then we say that the atom absorbed an incident photon. As a result of this absorption the atom jumps to the excited state E_2. This process is called induced absorption. This process may be represented as

$$A + h\upsilon \rightarrow A^*$$

where A denotes an atom in the lower state and A^* an excited atom.

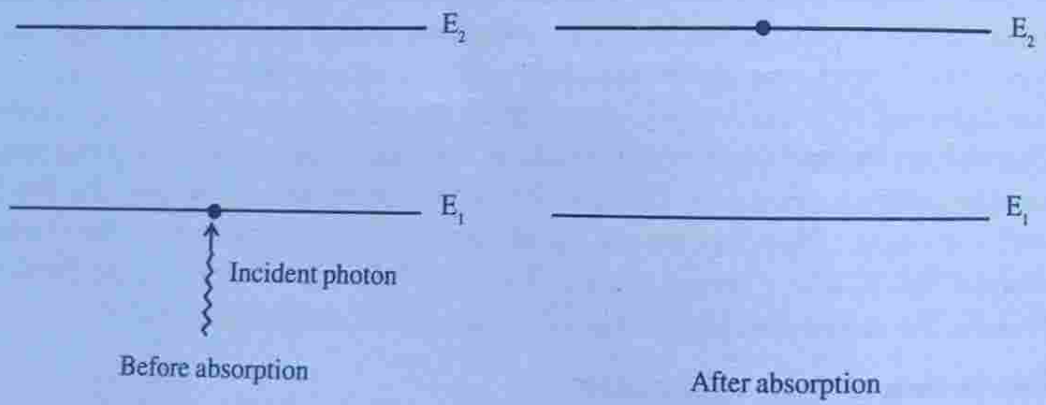

Figure 6.2

The number of atoms per unit volume that makes upward transitions from the lower level to the upper level per second is called the rate of absorption transition. It is represented by

$$R_{abs} = -\frac{dN_1}{dt} 0$$

where $-\frac{dN_1}{dt}$ stands for the rate of decrease of population at the lower level. The rate of absorption transition can also be represented by the rate of the increase of population at the upper level E_2. Thus

$$R_{abs} = \frac{dN_2}{dt}$$

$$\therefore \quad R_{abs} = -\frac{dN_1}{dt} = \frac{dN_2}{dt}$$

The number of absorption transitions occuring in the material at any instant will be proportional to the population in the lower level and the number of photons per unit volume in the incident beam. The rate of absorption may be expressed as

$$R_{abs} = B_{12}u(\upsilon)N_1$$

where B_{12} is a constant of proportionality and $u(\upsilon)$ is the energy density of incident light. B_{12} is known as the Einsteins coefficient for induced absorption and it indicates the probability of induced transition from level 1 to 2.

It may be noted that at thermal equilibrium, the population in the lower energy state is far larger than in the higher energy state. Therefore, as light propagates through the medium, it gets absorbed

Spontaneous emission

An atom cannot stay in the excited state for a long time. In about 10^{-8} s, the atom comes back to the lower state E_1 by releasing a photon of energy $h\upsilon = E_2 - E_1$. This emission of photon occurs on its own and without any external impetus given to the excited atom is called spontaneous emission. This process is represented as

$$A^* \rightarrow A + h\upsilon$$

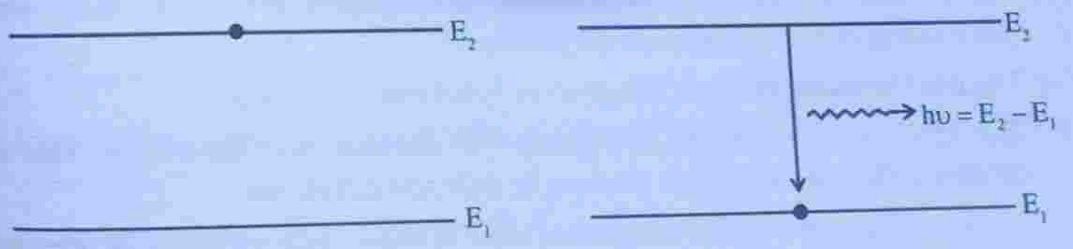

Figure 6.3

The rate of spontaneous transitions R_{sp} is given by

$$R_{sp} = -\frac{dN_2}{dt} = \frac{N_2}{\tau_{sp}} \qquad \ldots\ldots (1)$$

where τ_{sp} is the average life time in the excited level.

The number of photons generated will be proportional to the population of the excited level only and can be expressed as

$$R_{sp} = A_{21} N_2 \qquad \ldots\ldots (2)$$

where A_{21} is known as the Einstein coefficient for spontaneous emission. It is a function of frequency and properties of material. It indicates the probability of spontaneous transition from level 2 to 1. It may be noted that the spontaneous emission is independent of the light energy.

Comparing eqns (1) and (2) we get

$$A_{21} = \frac{1}{\tau_{sp}} \qquad \ldots\ldots (3)$$

or $$\tau_{sp} = \frac{1}{A_{21}}$$

i.e., The reciprocal of probability of spontaneous emission gives the life time. Life time is the average time for which the excited atom would remain in the upper level before undergoing spontaneous transition. It may also be noted that the rate of spontaneous transitions from E_1 to E_2 is zero.

i.e., $$A_{12} = 0$$

Characteristics of spontaneous emission

(i) This process is probabilistic in nature, hence cannot control from outside.

(ii) The instant of transition, direction of propagation, the initial phase and polarisation of each photon are all random.

(iii) The light resulting through this process is not monochromatic.

(iv) The light intensity goes on decreasing with distance from the source. This is because different atoms emit photons in different directions.

(v) It is due to the superposition of waves of random phase, light emitted is incoherent.

Stimulated emission

An atom in the excited state need not wait for spontaneous emission of photon. Suppose a photon of energy $h\upsilon = E_2 - E_1$ interacts with an excited atom at the energy level E_2 before its spontaneous emission take place. Then the excited atom at energy level E_2 makes a downward transition to energy level E_1 by releasing two photons each of energy $h\upsilon$. This process is called stimulated emission. Thus the phenomenon of forced photon emission by an excited atom due to the action of external agency is called stimulated emission or induced emission.

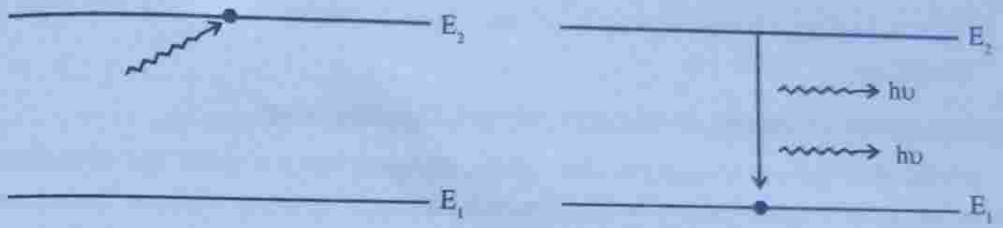

Figure 6.4

The process may be represented as

$$A^* \rightarrow A + 2h\upsilon$$

The probability that a stimulated transition occurs is given by

$$(p_{21})_{st} \propto u(\upsilon) \text{ or } (p_{21})_{st} = B_{21}u(\upsilon)$$

The rate of stimulated emission is given by

$$R_{st} = B_{21}\, u(\upsilon) N_2$$

where B_{21} is the Einstein coefficient for stimulated emission. It indicates the probability of stimulated emission transition from level 2 to level 1.

Characteristics of stimulated emission

(i) This process is controllable from outside.

(ii) The proton induced in this process propagates in the same direction as that of stimulating photon.

(iii) The inducing photon and the induced photon are identical in frequency, phase and plane of polarisation.

(iv) In this process photons get multiplied. One photon interacting with an excited atom, two photons are produced. These two photons travelling in the same direction interact with two more excited atoms, totally four photons are produced.

The process continues and get large number of photons like avalanche like manner.

(v) All the light waves generated in the medium are due to one initial wave and all of the waves are in phase. Thus the waves are coherent and interfere constructively. It results in light amplification.

(vi) The net intensity of light emitted will be proportional to the square of atoms radiating light. Thus

$$I_{total} = N^2 I$$

This means that light emitted is of very high intensity so we can say light is amplified.

Spontaneous emission dominates stimulated emission

All the three processes namely absorption, spontaneous emission and stimulated emission occur simultaneously in a medium, when light interacts with medium (matter). Under steady state condition the absorption and the emission processes balance each other.

Thus, $R_{abs} = R_{sp} + R_{st}$

i.e., $B_{12}u(\upsilon)N_1 = A_{21}N_2 + B_{21}u(\upsilon)N_2$ ..... (4)

If we consider a medium in thermal equilibrium. In this condition there are more number of atoms in the lower level than the higher level. That is $N_1 \gg N_2$. Since the probability for absorption transition (B_{12}) is equal to the probability for stimulated transition (B_{21}), a photon travelling through the medium is more likely to get absorbed than to stimulate an excited atom to emit a photon. Therefore, usually the process of absorption dominates the process of stimulated emission. Similarly, an atom that is at the excited state is more likely to jump to the lower level on its own than being stimulated by a photon. It is due to the fact that the photon density in the incident beam is not sufficient to interact with the excited atoms and the photons interact with atoms at lower level because of the large population available at that level. Owing to this, the spontaneous emission dominates the stimulated emission.

Einstein coefficients

(i) We found that the probability that an absorption transition is given by

$$P_{12} \propto u(\upsilon)$$

i.e., $$P_{12} = B_{12}u(\upsilon)$$

The constant of proportionality is known as the Einstein a coefficient for induced absorption. It is a constant characteristic of the atom and represents the properties of the energy states E_1 and E_2.

(ii) The probability that a spontaneous transition is given by

$$(P_{21})_{sp} = A_{21}$$

where A_{21} is a constant known as Einstein coefficient for spontaneous emission. A_{21} is a constant characteristic of the atom and is known as the radiative rate.

$\frac{1}{A_{21}}$ is the life time of the upper state against spontaneous decay to the lower state.

(iii) The probability that a stimulated transition occurs is given by

$$(P_{21})_{st} \propto u(\upsilon)$$

or $$(P_{21})_{st} = B_{21} u(\upsilon)$$

where B_{21} is the constant of proportionality known as the Einstein coefficient for stimulated emission. It is a constant characteristic of the atom and represents the properties of the states E_1 and E_2.

***Note*:** The spontaneous transition from the state E_1 to E_2 is forbidden by quantum mechanics $A_{12} = 0$.

Relation between Einstein coefficients

Consider an assembly of atoms in thermal equilibrium at temperature with radiation of frequency υ and energy density $u(\upsilon)$. Let N_1 and N_2 be the number of atoms in energy levels 1 and 2 respectively at any instant. At thermal equilibrium N_1 and N_2 in their levels must remain constant. The condition required that the number of transitions from E_2 to E_1 must be equal to the number of transitions from E_1 to E_2. Thus

The number of atoms absorbing photons per second per unit volume = The number of atoms emitting photons per second per unit volume

The number of atoms absorbing photons per second per unit volume $= B_{12} u(\upsilon) N_1$

The number of atoms emitting photons per second per unit volume $= A_{21} N_2 + B_{21} u(\upsilon) N_2$

So in equilibrium, we have

$$B_{12}u(\upsilon)N_1 = A_{21}N_2 + B_{21}u(\upsilon)N_2$$

or $$B_{12}u(\upsilon)N_1 - B_{21}u(\upsilon)N_2 = A_{21}N_2$$

$$u(\upsilon)(B_{12}N_1 - B_{21}N_2) = A_{21}N_2$$

$$u(\upsilon) = \frac{A_{21}}{B_{12}N_1 - B_{21}N_2}$$

$$u(\upsilon) = \frac{A_{21}N_2}{B_{12}\frac{N_1}{N_2} - B_{21}}$$

$$u(\upsilon) = \frac{\frac{A_{21}}{B_{12}}}{\frac{N_1}{N_2} - \frac{B_{21}}{B_{12}}}$$

According to Boltzmann's distribution law, we have

$$\frac{N_1}{N_2} = e^{\frac{(E_2 - E_1)}{kT}} = e^{\frac{h\upsilon}{kT}}$$

$$\therefore \quad u(\upsilon) = \frac{\frac{A_{21}}{B_{12}}}{e^{\frac{h\upsilon}{kT}} - \frac{B_{21}}{B_{12}}} \qquad \ldots\ldots (1)$$

According to Planck's radiation formula we have

$$u(\upsilon) = \frac{8\pi h\upsilon^3}{c^3}\left(\frac{1}{e^{\frac{h\upsilon}{kT}} - 1}\right) \qquad \ldots\ldots (2)$$

Comparing eqns (1) and (2) we get

$$\frac{A_{21}}{B_{12}} = \frac{8\pi h\upsilon^3}{c^3} \qquad \ldots\ldots (3)$$

and $$\frac{B_{21}}{B_{12}} = 1$$

or $$B_{21} = B_{12} \qquad \ldots\ldots (4)$$

Equations 3 and 4 are known as Einsteins relations.

Equation (3) says that the ratio of coefficients of spontaneous emission to the coefficient of stimulated emission is proportional to υ^3. It means that the probability of spontaneous emission dominates over stimulated emission more and more as the energy difference between two levels ($h\upsilon$) increases. This is why it is difficult to achieve laser action in higher frequency ranges such as X-rays.

Equation (4) says that the coefficients for both absorption and stimulated emission are equal. i.e., the probability of absorption transition is same as the probability of stimulated emission transition. This implies that when an atom with two energy levels is placed in a radiation field, the probability for an upward (absorption) transition is equal to the probability for a downward (stimulated emission) transition.

Light amplification

We found that when medium is in thermal equilibrium spontaneous emission dominates the stimulated emission. Light amplification requires that stimulated emission occur almost exclusively. In practice, absorption and spontaneous emission always occur together with stimulated emission. The laser operation is achieved when stimulated emission exceeds the other two processes extensively, we shall see under what conditions this criterion is met with.

Condition for stimulated transition to dominate over both spontaneous and absorption transition

For the laser action to take place the existence of stimulated emission is essential. In practice, the absorption and spontaneous emissions always occur together with stimulated emission. Here we shall see under what conditions the number of stimulated emissions can be made larger than the other two processes. The ratio of stimulated transitions to spontaneous transitions is given by

$$R_1 = \frac{\text{Stimulated transitions}}{\text{Spontaneous transitions}} = \frac{B_{21}u(\upsilon)N_2}{A_{21}N_2}$$

i.e., $$R_1 = \frac{B_{21}u(\upsilon)}{A_{21}}$$

For the stimulated emission transition to be large R_1 must be large i.e., $\frac{B_{21}}{A_{21}}$ must be large and $u(\upsilon)$ must be large. The ratio of stimulated transitions to absorption transitions is given by

$$R_2 = \frac{\text{Stimulated transitions}}{\text{Absorption trnasitions}}$$

$$R_2 = \frac{B_{21}u(\upsilon)N_2}{B_{12}u(\upsilon)N_1} = \frac{N_2}{N_1}$$

For the stimulated transition to be large R_2 must be large $(R_2 \gg 1)$

i.e., $$\frac{N_2}{N_1} \gg 1$$

or $$N_2 \gg N_1$$

i.e., the population N_2 of the excited state should be larger than the population N_1 of the lower energy level.

The above discussion shows that to make stimulated transitions overwhelm the other transitions, three conditions are to be satisfied.

(i) The population at excited level should be greater than at the lower energy level

(ii) The ratio $\frac{B_{21}}{A_{21}}$ should be large.

(iii) The radiation density $u(\upsilon)$ present in the medium must be high.

When these three conditions are satisfied a medium amplifies light.

Our next aim is to see how to achieve the three above said conditions. The first condition $(N_2 > N_1)$ can be met by a mechanism called population inversion. The second condition $\left(\frac{B_{21}}{A_{21}} \text{is larger}\right)$ is achieved by choosing a metastable energy level as the higher energy level. This is because, spontaneous transitions are forbidden from metastable state, then $\frac{B_{21}}{A_{21}}$ will be larger. To achieve the third condition

$(u(\upsilon)$ is higher) enclose the emitted radiation in an optical resonant cavity formed by two parallel mirrors. The radiation is reflected many times till the photon density $(u(\upsilon))$ reaches to a very high value. Now we will see the three above said mechanisms in detail.

Population inversion

When an atomic system is in thermal equilibrium, photon absorption and emission processes take place side by side. Since $N_1 > N_2$ absorption dominates. For laser action to take place stimulated emission must dominate over the other two. To have more stimulated emission than absorption, a majority of atoms should be at the higher energy level than at the lower level. Through some mechanism we can make the number of atoms in the excited level very much greater than that in the ground level. i.e., $N_2 > N_1$. This is a non-equilibrium condition and is known as inverted population condition. This state of the medium is known as the population inversion. Thus population inversion is the non-equilibrium state of the material in which population of the higher energy level N_2 exceeds the population of the lower energy level N_1.

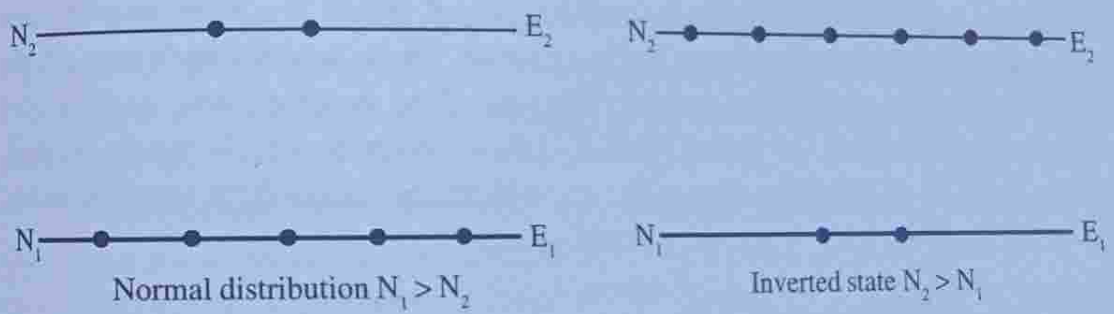

Figure 6.5

Extending the Boltzmann's distribution law

$$\frac{N_2}{N_1} = e^{-\frac{(E_2 - E_1)}{kT}} = e^{-\frac{h\upsilon}{kT}}$$

To this non equilibrium state of population inversion, it is seen that N_2 can exceed N_1 only if the temperature were negative. In view of this, the state of population inversion is sometimes referred to as a negative temperature state. It does not mean that we can attain temperatures below absolute zero. This happens because the state of population inversion is a non-equilibrium state and the law is not applicable to this. It should be borne in mind that the population inversion state is attained at normal temperatures.

Meta stable state

Population inversion can be achieved through pumping. Since the life time of excited atoms is 10^{-8}s, they release their energy through spontaneous emission. It means that atoms cannot stay in the excited state for a long time. i.e., population inversion cannot be achieved. In order to achieve population inversion atoms have to wait in the excited state till a large number of atoms accumulate in that level. In otherwords population inversion can be achieved in an excited state which has a longer life time. Such a state is called metastable state.

The metastable state has lifetime of the order of 10^{-6} to 10^{-3}s. Metastable state is necessary for laser action.

Componentes of laser

The essential components of a laser are (i) an actaive medium (ii) a pumping agent and (iii) an optical resonator.

Active medium

Atoms in general are characterised by a large number of energy levels. However, all types of atoms are not suitable for laser operation. Even in a medium consisting of different species of atoms, only a small fraction of atoms of a particular species are suitable for stimulated emission and laser action. Those atoms which cause light amplification are called active centres. The rest of the medium acts as host and supports active medium. An active medium is thus a medium which, when excited, reaches the state of population inversion, and eventually causes light amplification. The active medium may be a solid, a liquid or a gas.

Pump

For achieving population inversion we have to transfer atoms from the lower energy level to the upper energy level. For this energy must be supplied to the medium. This process of supplying energy to the medium to achieve population inversion is called pumping. There are several methods of pumping. They are optical pumping, electrical pumping, direct conversion are some of them.

Optical pumping

In optical pumping a light source such as a flash discharge tube is used to illuminate the laser medium and the photons of appropriate frequency excite the atoms to an upper most level. From there, they drop to the metastable upper laser level to create the state of population inversion.

Optical pumping sources are flash discharge tubes, continuously operating lamps, spark gaps or an auxillary laser is sometimes used as the pump source.

Optical pumping is suitable for any laser medium which is transparent to pump light. Optical pumping is used for solid state crystalline lasers and liquid tunable dye lasers.

Electrical pumping

Electrical pumping can be used only in case of laser materials that can conduct electricity. This method is limited to gases. In case of a gas laser, a high voltage pulse initially ionises the gas so that it conducts electricity. An electric current flowing through the gas excites atoms to the excited level from where they drop to the metastable upper laser level leading to population inversion.

Direct conversion

In semiconductor lasers, a direct conversion of electrical energy into light energy takes place. Here it is not the atoms that are excited. It is the current carriers namely electrons and holes which are excited and a population inversion is achieved in the junction region. The electrons recombine with holes in the junction regions producing laser light.

Optical resonant cavity

Laser is an amplified light source. In electronics signals are amplified by an oscillator with positive feedback. A mechanism similar to this is required to amplify light. In laser the active medium is the amplifying medium. This medium is converted into an oscillator through feedback mechanism established by a device called an optical resonator.

For the medium to act as an oscillator, a part of the output energy must be feedback into the system. Such a feedback is brought about by placing the active medium between a pair of mirrors which are facing each other. The mirrors could be either plane or curved. Such a system formed by a pair of mirrors is referred to as a resonator.

If the mirrors used are plane, it is called a plane parallel resonator. A plane parallel resonator consisting of a pair of plane mirrors facing each other. The active medium is placed inside the cavity. This constitutes an optical resonant cavity.

One of the mirrors is fully reflecting and reflects all the light that is incident on it. The other mirror is made partially reflecting such that 90% of incident light is reflected from it and a small fraction is transmitted through it as the laser beam.

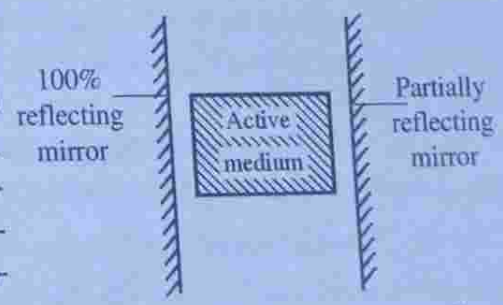

Figure 6.6 : Optical resonant cavity

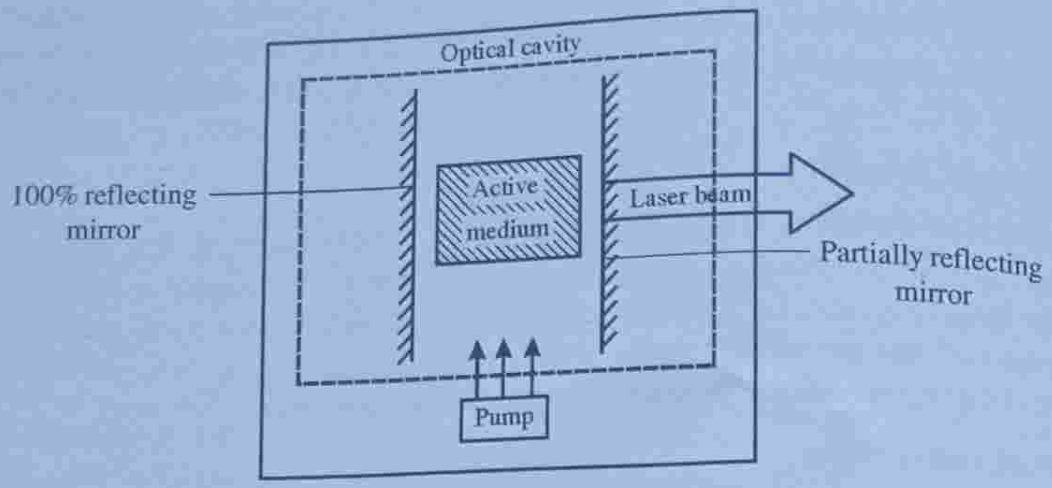

Figure 6.7 : Laser components

Lasing action

Initially, the active centres in the medium are in the ground state. Through suitable pumping mechanism the medium is taken into the state of population inversion. i.e., the excited states are more populated than the ground state. Now some of the excited atoms emit photons spontaneously in various directions. Each spontaneous photon can trigger many stimulated transitions along the direction of its propagation. The photons stimulated travel in different directions since the cause of it travel in different directions. Many such photons leave the medium without reinforcing their strength, resulting in incoherent light. However the presence of mirror impose a specific direction on photons. Photons travelling along the axis are amplified through stimulated emission while photons emitted in any other direction will pass through the sides of the medium and lost for ever. Thus a specific direction is selected for further amplification.

It is due to photons back and forth reflection between the mirrors large number of times, stimulated emission increases sharply there by achieving light amplification.

Since the mirrors provide a feedback of light into the medium, the stimulated emission acts are sustained and the medium operates as an oscillator. At each reflection at the front mirror light is partially transmitted through it. Owing to this energy losses from the resonator. This loss of energy and that from the medium will over whelmed by the increase in the stimulated emission, laser oscillations buildup. Finally a steady and strong laser beam will emerge from the front mirror.

As the front mirrors reflect light into the medium, energy density of light $u(\upsilon)$ is large in the medium. See also the the figure below.

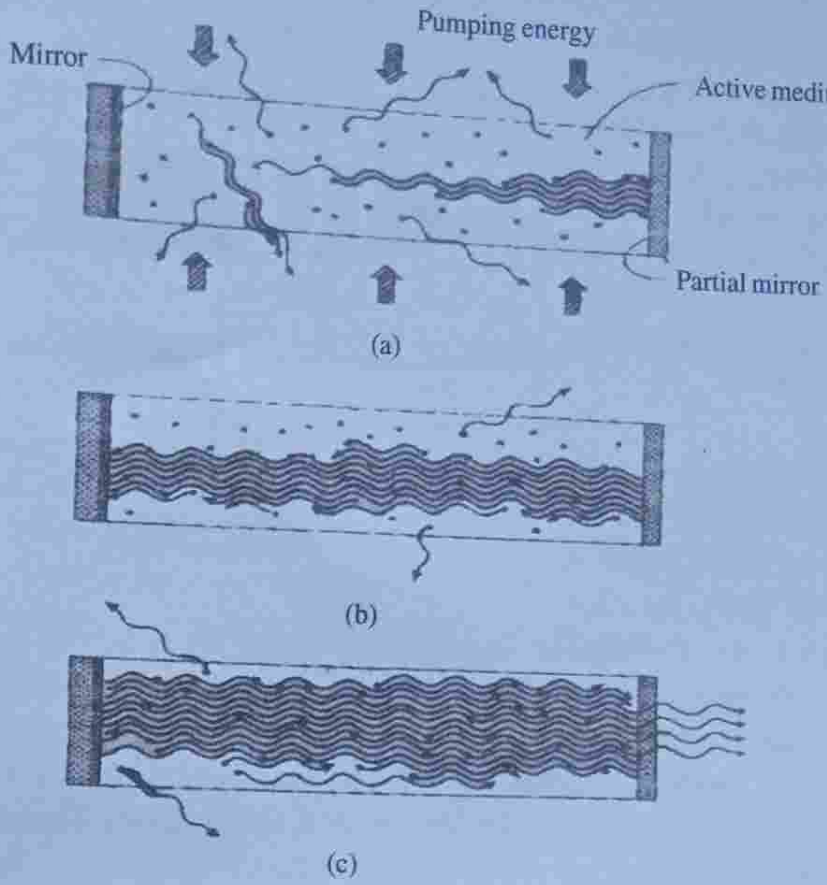

Figure 6.8 : Lasing action

Types of lasers

There are several ways of classifying lasers. We here prefer to classify the lasers on the basis of the material medium used. Accordingly they are divided into four (i) solid state lasers (ii) gas lasers (iii) liquid lasers and (iv) semiconductor diode lasers.

Ruby laser : (A solid state laser)

Theodore Maiman of U.S.A in 1960 fabricated the first laser using a ruby crystal. The ruby crystal rod is a crystal of aluminium oxide doped with chromium ions at a concentration of about 0.05% by weight.

Construction

The ruby laser consists of a cylindrical crystal rod of ruby of about 4cm in length and 0.5cm in diameter whose ends are flat and one of which is completely silvered and the other partially silvered. The silvered ends thus form a resonant cavity. The ruby rod is placed inside a helical photographic flash lamp filled with xenon called

xenon lamp. The xenon flash lamp is connected to a capacitor which discharges a few thousand joules of energy in a few milliseconds. This results in a power output of a few megawatts. The flash lamp acts as the optical pumping system.

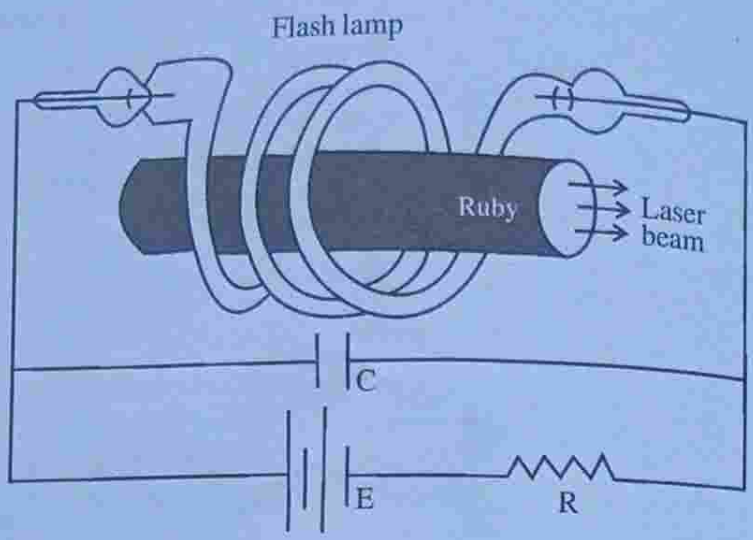

Figure 6.9

Working

When the flash lamp is switched on, xenon discharge generates an intense burst of white light lasting for a few milliseconds. The Cr^{3+} ions are excited to the energy bands E_1 and E_2 by the blue and green components of white light. The energy levels in these bands have a very small life time ($\approx 10^{-9}$ s). Hence the excited Cr^{3+} ions undergo non radiative transitions and drop to the metastable state M. The metastable state is having a life time of nearly 1000 times more than the life time of E_1 and E_2 levels. Therefore Cr^{3+} ions accumulate at M level. When more than half of the Cr^{3+} ion population accumulates at E_2 level, the population inversion is achieved between states M and G (ground state). A chance photon emitted spontaneously by a Cr^{3+} ions initiates a chain of

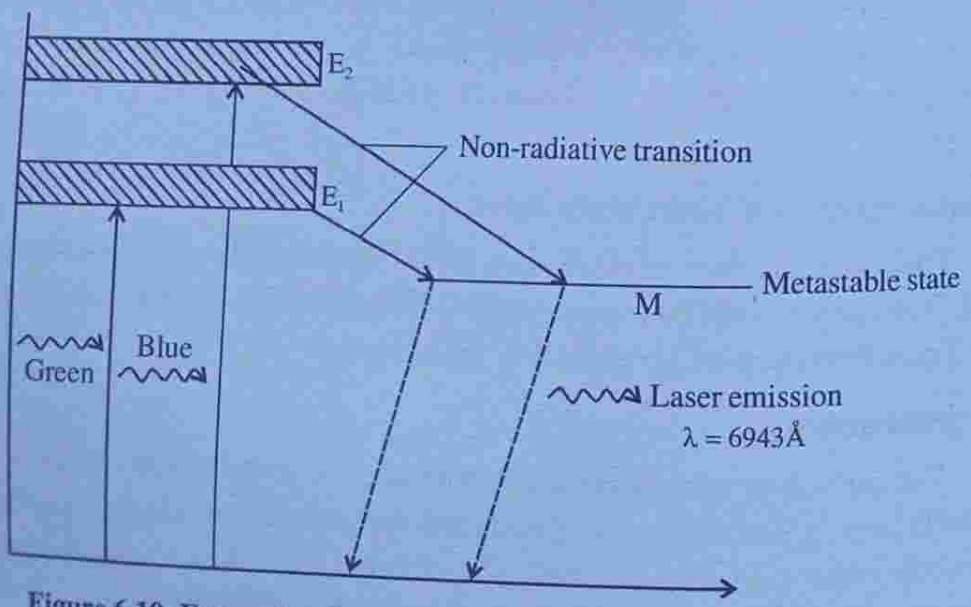

Figure 6.10: Energy levels and transitions in a ruby laser

stimulated emissions by Cr^{3+} ions in the metastable state. Red photons of wave length 6943Å travelling along the axis of the ruby rod are repeatedly reflected at the end mirrors and light amplification takes place. A strong intense beam of red light emerges out of the front end mirror.

Helium-Neon Laser

Ali Javan and his co-workers in Bell Telephone Laboratories in USA fabricated the first gas laser in 1961. A mixture of helium and neon was taken as the laser medium and electric discharge was used for optical pumping.

Construction

The helium-neon laser consists of along and narrow discharge tube of length 80 cm and diameter 1cm is filled with a mixture of helium and neon in the ratio 10:1. The gas mixture of helium and neon forms the lasing medium and this mixture is enclosed between a set of mirrors forming a resonant cavity. One of the mirrors is completely reflecting and the other is partially reflecting so as to take out the laser beam. The discharge tube is filled with electrodes to provide discharge in the gas. The electrodes are connected to high voltage (10kV) power supply.

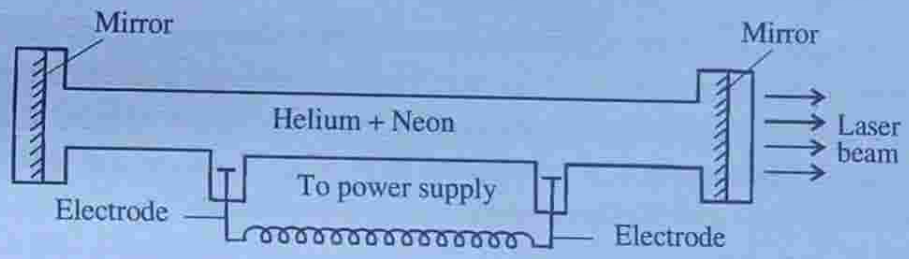

Figure 6.11

Working

When the power is switched on, discharge takes place inside the tube. The electrons and ions produced in the process of discharge are accelerated towards the respective electrodes. The energetic electrons collide with the helium atoms and excite them to higher energy levels F_2 and F_3. These levels happens to be metastable and hence they stay therefore a long time. i.e. excited atoms cannot return to the ground level through spontaneous emission. However it can return to the ground level by transferring its excess energy to a neon atom through collision. As a result neon atoms are excited to the levels E_4 and E_6 which have approximately the same energy as that of F_2 and F_3 of helium. Thus the discharge through the gas mixture continuously populates the neon excited energy levels E_4 and E_6. E_4 and E_6 are metastable states. This helps to create a state of population inversion between the level

E_6(or E_4) and the lower energy level E_5 (or E_3). The various transitions (see figure) lead to emission at wavelengths of 3.39μm, 1.15μm and 6328 Å . The first two correspond to infrared region while the last one corresponds to red light. Specific frequency selection may be obtained by employing mirrors which reflect only a small band of frequencies about the frequency of interest.

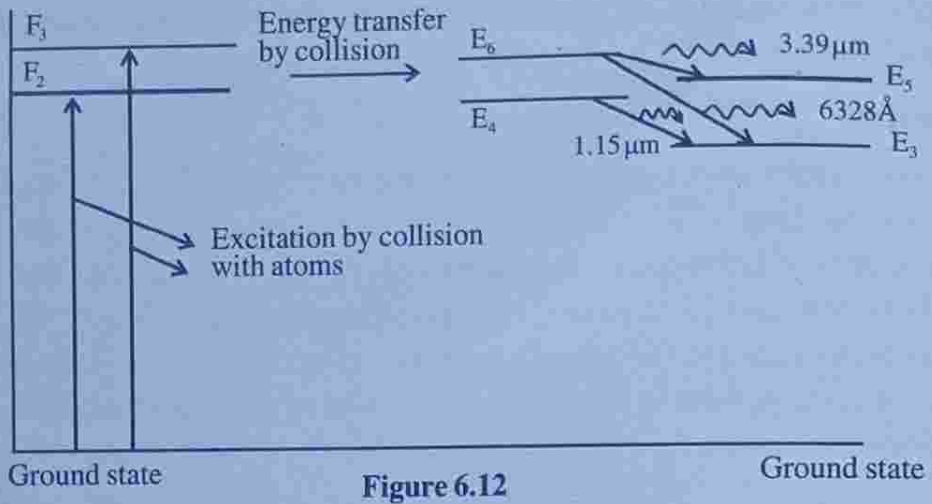

Figure 6.12

The typical power output of helium-neon lasers lie between 1 and 50 mW. The gas lasers are more directional and more monochromatic compared to that of solid state lasers. The gas lasers can supply continuous laser beam without the need for elaborate cooling arrangement. One disadvantage of gas lasers is that the mirrors are usually eroded by the gas discharge and have to be replaced.

Semiconductor laser

The first semiconductor laser was fabricated by R.N Hall and his coworkers in 1962. *A semiconductor diode laser is a specially fabricated PN junction device, which emits coherent light when forward biased.*

How to achieve population inversion in semiconductors

Population inversion is required for producing stimulated emission. A semiconductor consists of electrons and holes distributed in respective energy bands. Therefore the laser action in semiconductors involves energy bands rather than discrete levels. In other lasers population inversion is obtained by exciting electrons in spatially isolated atoms. In semiconductors, electrons are not associated with specific atoms but are injected into the conduction band from the external circuit. Therefore, the conduction band plays the role of excited level while the valence band plays the role of ground level. Population inversion required the presence of a large concen-

tration of electrons in the conduction band and a large concentration of holes in the valence band. A simple way to achieve population inversion is to use a semiconductor in the form of a PN junction diode formed from heavily doped P and N type semiconductors.

Construction

A diode laser consists of a heavily doped P-N junction. Starting with a heavily doped N type GaAs material, a P-region is formed on its top by diffusing Zinc atoms into it. A heavily Zinc doped layer constitutes the heavily doped P-region. The top and bottom faces are metallized and metal contacts are provided to pass current through the diode. The front and rear faces are polished parallel to each other and perpendicular to the plane of the junction. The polished faces serve as optical cavity. In practice there is no need to polish the faces. A pair of parallel planes cleared at the two ends of the PN junction provides the required reflection to form cavity. The two remaining sides of the diode are roughened to eliminate lasing action in that direction. The entire structure is packed in small case which looks like the metal case.

Working

When the P-N junction is forward biased, electron and holes are injected into the junction region in high concentrations. At low forward current level, the electron hole recombination causes spontaneous emission of photons and the junction acts as an LED. As the forward current through the junction is increased the intensity of the light increases linearly. However, when the current reaches a threshold value, the carrier concentrations in the junction region will rise to a very high value. As a result the junction region contains a large concentration of electrons within the conduction band and simultaneously a large number of holes within the valence band. Hole represent absence of electrons. Thus the upper energy level in the narrow region are having a high electron population while the lower energy levels in the same region are vacant. Therefore, the condition of population inversion is attained in the narrow junction region.

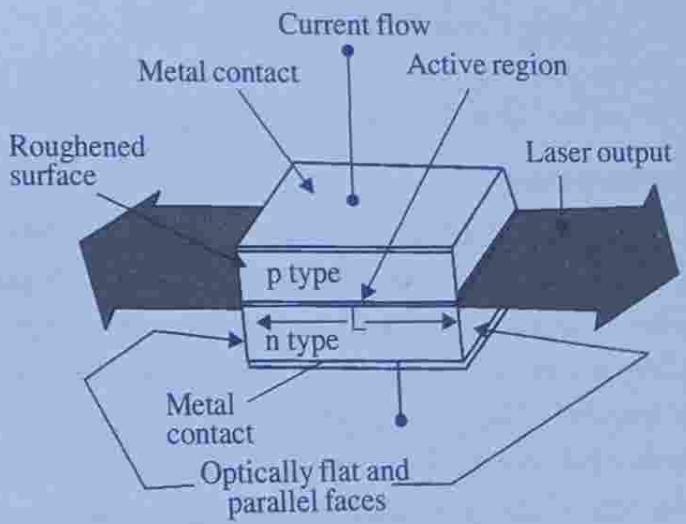

Figure 6.13

This narrow zone in which population inversion occurs is called an inversion region or active region. Chance recombination acts of electron and hole pairs lead to emission of spontaneous photons. The spontaneous photons propagating in the junction plane stimulate the conduction electron to jump into the vacant states of valence band. This stimulated electron hole recombination produces coherent radiation. GaAs laser emits light at a wavelength of 9000Å in IR region

Advantages of diode laser

(i) It is operated at low temperature

(ii) PN junction lasers are made to emit light almost anywhere in the spectrum from UV to IR

(iii) They are remarkably small in sizes (0.1mm long)

(iv) They have high efficiency of the order of 40%

(v) They operate at low powers

(vi) It is portable

(vii) They produce high power output

(viii) Their costs are cheap

Uses

The diode lasers are mass produced for use in optical fibre communications, in CD players, CD-ROM drivers, optical reading, high speed laser printing etc.

YaG laser

Yttrium Aluminium Garnet (UAG) crystal is doped with neodymium (Nd) ion, we get a laser medium. When doped in YAG, Nd^{+3} ions take the place of yttrium ions. Doping Concentrations are typically of the order of 0.725% by weight which corresponds to about 1.4×10^{26} atoms per cubic metre. These lasers are four level systems and therefore require lower pump energies than the ruby laser.

Construction

It consists of a laser rod (Nd : YAG) about 10cm in length and a diameter of 12 mm. The YAG rod and a linear flash lamp are housed in a reflector cavity of elliptical cross section. The light issuing from the lamp is closely coupled to the laser rod as they are located at the foci of the ellipse. The ends of the YAG rod are ground flat and parallel. The optical cavity may be formed by silvering the ends of the rod. In practice two external mirrors are used as shown in figure. One mirror is made 100% reflecting while the output mirror is about 90% reflecting. The system is cooled by circulating air.

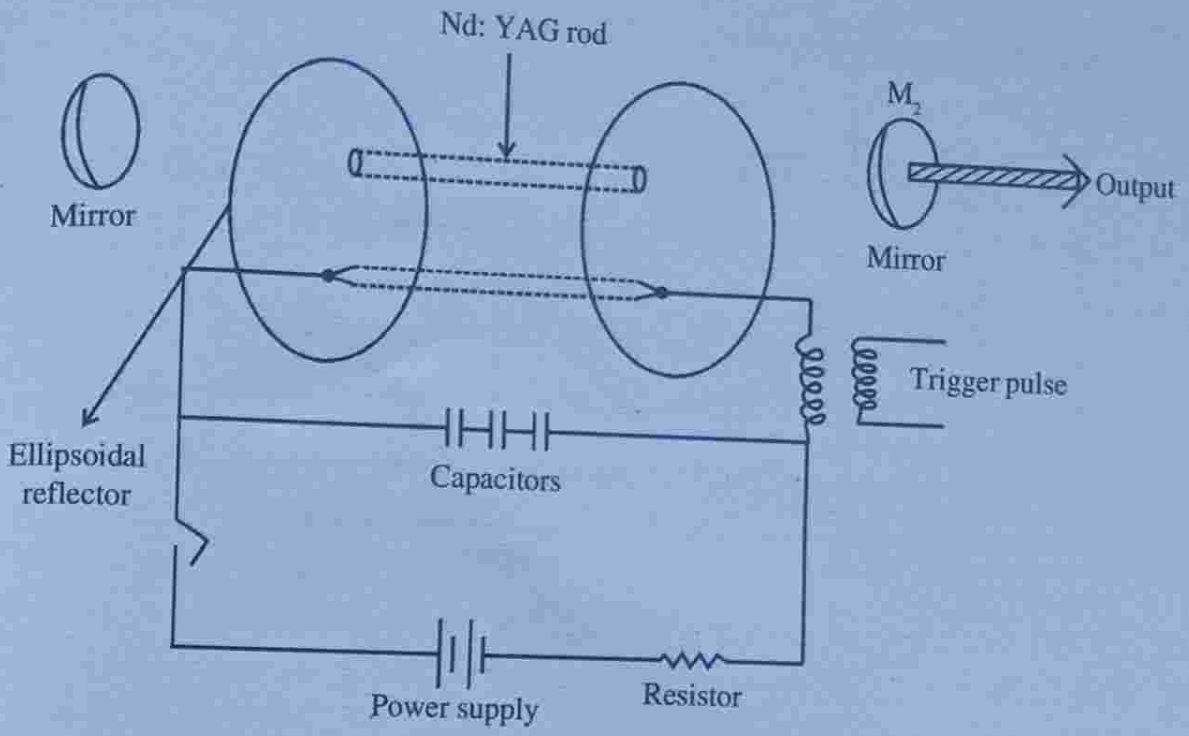

Figure 6.14

Working

It is a four level laser system. Here pumping is achieved by using an intense flash of white light from a xenon flash lamp. It excites Nd^{3+} ions from the ground state to the multiple energy state at E_4. The excited Nd^{3+} ions quickly decay to the meta-stable level E_3, releasing their excess energy to the crystal lattice. As the lower laser level E_2 is located at 0.25 eV above the ground state E_1, it cannot be populated by Nd^{3+} ions through thermal transitions from the ground level. The population inversion can be readily achieved between E_3 and E_2 levels. In the E_3 level, Nd^{3+} ions are stimulated to emit on the main 1.064μm laser transaction and drop to the lower laser level E_2. From the level E_2, Nd^{3+} ions quickly drop to the ground state again by transferring energy to the crystal. The output power of the laser is about 1kW. The wavelength of this laser lies in the infra red. It is possible to double the frequency by second harmonic generation. Therefore, through a harmonic generator to the system, this laser can be made to produce green light at a wavelength of 5320Å.

Characteristics of Laser beam

The important characteristics of a laser beam are

1) directionality
2) negligible divergence

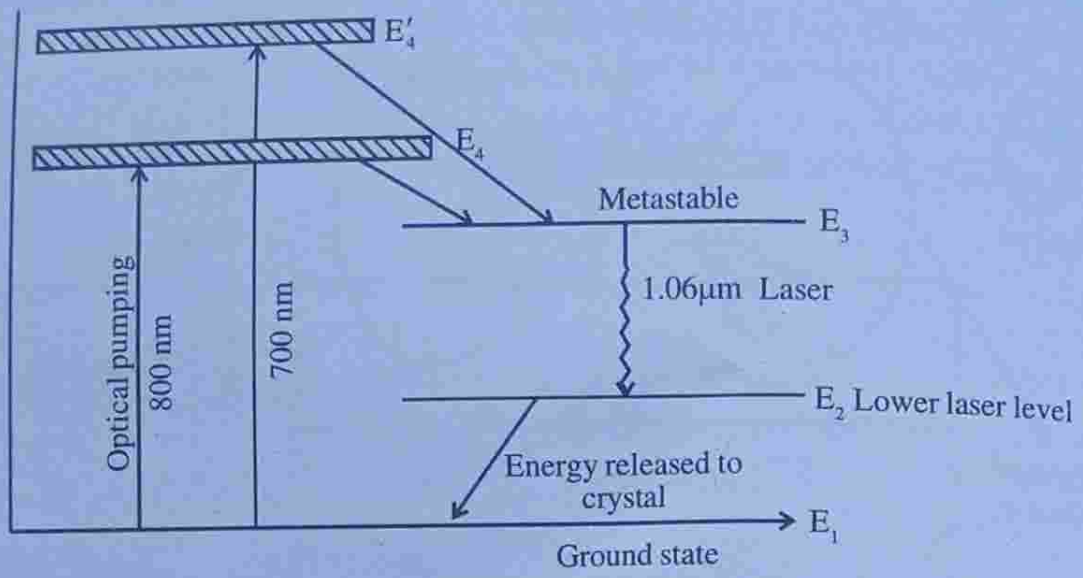

Figure 6.15

3) high intensity
4) high degree of coherence and
5) high degree of monochromaticity.

1) Directionality

The conventional light sources emit light in all directions. To have a beam in one direction source is place it before a narrow slit. The laser beam emits only in one direction called directionality.

2) Divergence

Light from conventional sources spread out in the form of spherical waves, hence it is divergent. Laser propagates in the form of plane waves. So divergence is very small. For example a typical He-Ne laser diverges about only 10^{-3} radian.

3) Intensity

The intensity of a conventional source of light decreases with distance. But the intensity of laser beam is almost a constant. Laser beam is highly intense.

4) Coherence

Conventional source of light is incoherent whereas laser light is highly coherent. For example light from a sodium lamp has a coherence length of 0.3mm where as coherence length of a typical He-Ne laser is about 100m.

5) Monochromaticity

When a light source has only one frequency (single wavelength) is called monochromatic and the source is called monochromatic source. Conventional monochro-

matic source spreads over a wavelength of 100Å to 1000Å where as laser beam spreads over a narrow range less than 10Å, so we say that laser sources are highly monochromatic.

Applications of laser

Lasers find applications in almost every field. They are used in mechanical working, industrial electronics, entertain electronics, communications, information processing and even in wars to guide missiles to the target. Lasers are used in CD players, laser printers, laser copiers, optical floppy discs, optical memory cards etc. Lasers are also used in medical field. It is used as a tool for surgical operations especially in ophthalmology and dermatology. Here we discuss only some of them.

(i) Welding

Welding is the process of joining two or more pieces into a single piece. If we consider welding of two metal plates, the metal plates are held in contact at their edges and a laser beam is made to move along the line of contact of the plates. The laser beam heats the edges of the two plates to their metal point and causes them to fuse together and become a single piece when the laser beam is removed. The main advantage of the laser is that it is a contact-less process and there is no possibility of introduction of impurities into the joint. In the process, the work pieces do not get disturbed, as the total amount of input is very small compared to conventional welding process. The heat effected zone is relatively small because of rapid cooling. Laser welding can be done even at a place difficult to reach. CO_2 lasers are used in welding thin sheets and foils.

Drilling

The principle of drilling is the vapourisation of metal at the focus of the laser beam. One can drill holes of diameter less than 10μm, For drilling, the energy must be supplied in such a way that rapid evaporation of material takes place without significant radial diffusion of heat into the work piece. The vapourised material is removed with the help of a gas jet. Pulsed ruby and neodymium lasers are commonly used for this. CO_2 lasers also used for drilling and cutting. This laser system is commonly used to drill and cut not only metals but also nonmetals such as ceramics, plastics, cloth, paper, glass and so on.

(ii) Hardening

Lasers are used to harden metals and other materials. Heat treatment is the process for this. Heat treating converts the surface layer to a crystalline state that is harder and more resistance to wear. Heat treatment is common in the tooling and automotive industry. It is used to strengthen cylinder blocks, gears, camshafts etc. in

the automobile industry. Usually CO_2 laser with 1kW output power is used for heat treatment.

(iii) Electronic industry

Lasers are used in the manufacture of electronic components and integrated circuits. Lasers have been used to perforate and divide silicon slices having several hundred circuits. They are also used for the isolation of faulty components in a large integrated circuit by disconnecting the conducting paths by evaporation. Trimming of thick and thin film resistors using lasers is a very common application.

(iv) Medical field

Surgeons use lasers to burn up brain tumours and tattoos. Lasers are also used in the treatment of paralysis. He-Ne laser is used to stimulate the nerves in the wrists and ankles. This is also used to stimulate the part of the brain that controls motor responses and causes dramatic change in nerve reactions.

In ophthalmology surgeons now a days use lasers to treat severe glaucoma patients. In dermatology surgeons use lasers to remove skin irregularities, warts, pimples and deep-red birthmarks.

Raman effect

When a beem of monochromatic light of frequency υ_0 is incident on dust free transparent liquids such as benzene, toluene, carbon tetra chloride etc. most of it is transmitted without change and some of it is scattered with a pair of frequencies of the type $\upsilon = \upsilon_0 \pm \upsilon_m$, where υ_m is the characteristic frequency of molecular system. This kind of scattered radiation with change of frequency is called Raman scattering and the phenomenon is called Raman effect.

Raman experiment and Raman spectrum

The original arrangement used by Raman was very simple in design. A round bottomed glass flask was filled with dust free organic liquid and the liquid strongly illuminated by 4358.3Å line from a mercury arc lamp, suitably filtered and concentrated by a lens. The scattered light was examined by means of a spectroscope placed in a direction perpendicular to that of the incident radiation. In the spectrum of scattered light, a number of new lines were observed on both sides of the main line. This is called the Raman spectrum. See the spectral profiles of Raman spectrum below. Raman spectrum consists of three types of lines or bands.

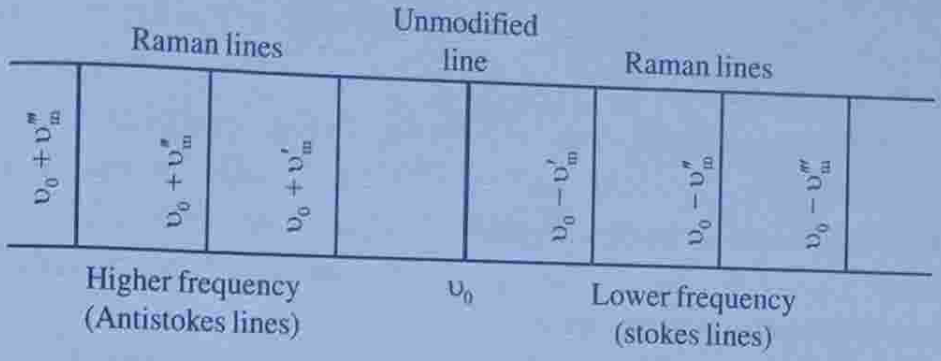

Figure 6.16: Profile of the Raman spectrum

1. Unmodified lines

This line occurs with no change in frequency from that of the illuminating line and corresponds to frequency υ_0. The frequency value of this line depends on the nature of the source used to irradiate the sample. It is a very intense line and lies exactly at the centre of the Raman spectrum about which the other Raman lines are symmetrically distributed.

2. Stokes lines

These corresponds to modified frequency bands which occur on the lower frequency side of the spectrum. The lines on this side are more numerous and more intense than those on the higher frequency side. These lines are indicated as $\upsilon_0 - \upsilon_m$ in the figure.

3. Antistokes lines

The lines indicated by $\upsilon_0 + \upsilon_m$ on the left side of the figure are called antistokes lines. They are less intense and less numerous when compared to the stokes lines. Owing to the gradual decline in intensity of these lines as we move away from the unmodified (υ_0) line in many instances it was not possible to detect as many lines as there are stokes lines in the Raman spectrum.

The new frequencies $\upsilon = \upsilon_0 \pm \upsilon_m$ in the spectum of scattered radiation are called Raman lines including υ_0. Another important aspect of the Raman spectrum is that most of these new lines are strongly polarised and their spacing is symetrical about the main line υ_0.

The original Raman experiment conducted by Raman consisted of dust free CCl_4 and the monochromatic incident source used for irradiation was mercury arc lamp with wavelength 4358.3Å or wave number $\frac{1}{\lambda} = \bar{\upsilon} = 22,938 cm^{-1}$. The Raman spectrum obtained on a photographic plate after a very long irradiation period, contained

one intense band at $\bar{\upsilon}_0 = 22,938\text{cm}^{-1}$ due to Rayleigh scattering and a number of weak bands at $\bar{\upsilon}_0 \pm 218$, $\upsilon_0 \pm 314$, $\bar{\upsilon}_0 \pm 459$, $\bar{\upsilon}_0 - 762$, $\bar{\upsilon}_0 - 790\text{cm}^{-1}$. The first three pairs of bands were easily detectable on the photographic plate. Only the stokes lines corresponding to $\bar{\upsilon}_0 - 762$ and $\upsilon_0 - 790\text{cm}^{-1}$ could be seen as very weak bands where their corresponding anti-stokes lines were not observed. However, with the availability of laser sources, Raman spectra are now being recorded in lesser time and with greater intensity bands.

Raman scattering versus Rayleigh scattering

Scattering of radiation without any change in frequency had been known earlier to the discovery of Raman effect. In general, scattering of radiation without any change in frequency can occur from very large scatterers like dust particles and such phenomenon was called Mie scattering. However, when a similar scattering occurs with molecules which are smaller than the wavelength of the incident radiation, it is called Rayleigh scattering, after its discoverer, Lord Rayleigh. In the Raman scattering a set of new discrete frequencies were observed when the scatterer was a molecule like in Rayleigh scattering. In Rayleigh scattering no frequency change takes place and only the existing frequencies appear. But in Raman scattering new lines of different frequencies were observed through a single incident frequency. Thus Rayleigh scattering always accompanies Raman scattering. Also, in the Rayleigh scattering although there is no resultant change in the energy state of the molecular system, the system will participate directly in the scattering act. This process causes one photon of incident radiation to be annihilated and a photon of the same energy to be created simultaneously. The intensity of Rayleigh lines is generally about 10^{-3} of the intensity of the incident line, where as the intensity of the strong Raman line is about 10^{-3} of the intensity of Rayleigh line.

Classical theory of Raman effect

This theory leads to an understanding of the vital concept, the molecular polarizability, though the theory is not fully adequate. When molecule is placed in a static electric field it suffers some distortion, the positively charged nuclei being attracted towards the negative of the field, the electrons to the positive of the field. This separation of charge centres causes an induced electric dipole moment to set up in the molecule and the molecule is said to be polarized. The magnitude of the induced dipole moment (μ_i) depends on the magnitude of the applied field (E) and on the ease with which the molecule can be polarized. Thus we have

$$\mu_i = \alpha E \qquad \ldots\ldots (1)$$

where α is the polarizability of the molecule.

Consider a diatomic molecule H_2 placed in an electric field (E) in two ways one perpendicular (end on or called equitorial) to the direction of the electric field other one along the direction of electric field as shown in figure.

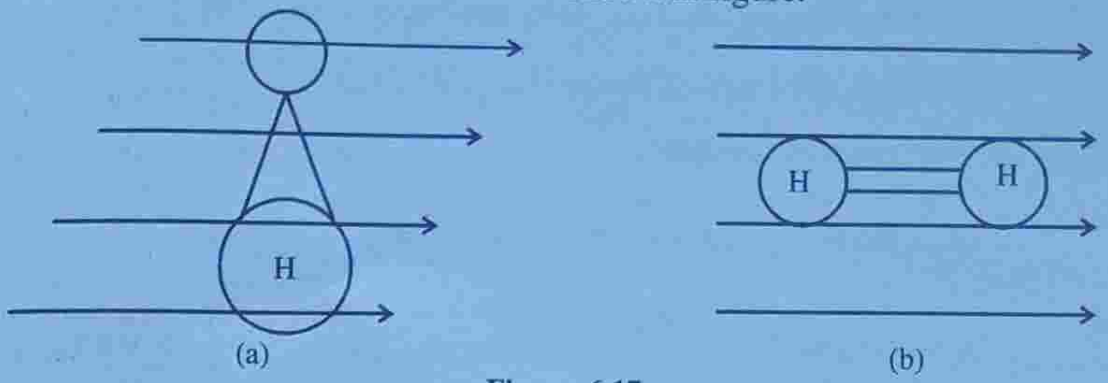

Figure 6.17

It is seen that the electrons forming the bond are more easily displaced by the field along the bond axis (figure b) than across the bond (figure a). Thus the polarizability is said to be anisotropic. Experimentally it has been found that the induced dipolemoment for a given field applied along the axis is approximately twice as large as that induced by the same field across the axis. The fields in other directions induce intermediate dipole moments.

Theory

When a polarized molecule is subjected to a beam of monochromatic radiation of frequency υ, the electric field experienced by each molecule varies according to the equation

$$E = E_0 = \sin 2\pi\upsilon t$$

$\therefore$ The induced dipolemoment becomes

$$\mu_i = \alpha E = \alpha E_0 \sin 2\pi\upsilon t$$

This equation shows that the induced dipole oscillates with a frequency υ. We know that an oscillating dipole emits radiation corresponding to the frequency of oscillation. This is the unshifted scattering of the incident radiation which gives the explanation of Rayleigh scattering.

In addition, if the molecular system undergoes some type of periodic internal motion, such as vibration or rotation, this may change the polarizability of the molecule periodically. Then the oscillating dipole will have superimposed upon it the vibrational or rotational oscillation. Consider, for example, a vibration of frequency υ_{vib} which changes the polarizability. We can write

$$\alpha = \alpha_0 + \beta \sin 2\pi\upsilon_{vib} t$$

where α_0 is the equilibrium polarizability and β is the rate of change of polarizability with the vibration. Thus we have

$$\mu_i = \alpha E = (\alpha_0 + \beta \sin 2\pi \upsilon_{vib} t)\ E_0 \sin 2\pi \upsilon t$$

$$\mu_i = \alpha_0 E_0 \sin 2\pi \upsilon t + \beta E_0 \sin 2\pi \upsilon_{vib} t \sin 2\pi \upsilon t$$

Using the trigonometric relation

$$\sin A \sin B = \frac{1}{2}[(\cos(A-B) - \cos(A+B)]$$

$$\mu_i = \alpha_0 E_0 \sin 2\pi \upsilon t + \frac{\beta E_0}{2} \cos 2\pi(\upsilon - \upsilon_{vib})t - \frac{\beta E_0}{2} \cos 2\pi(\upsilon + \upsilon_{vib})t$$

This equation shows that the oscillating dipole has frequency υ, $\upsilon - \upsilon_{vib}$ and $\upsilon + \upsilon_{vib}$.

If $\beta = 0$ in the above equation the dipole oscillates only at the frequency of the incident radiation. This shows that in order to have Raman lines $\beta \neq 0$. i.e., a molecular vibration must cause some change in a component of molecular polarizability (α). This is also true for molecular rotation.

The above discussion shows that the prerequisite to the Raman effect is the occurance of a periodic internal motion accompanied by the corresponding polarizability change. The change in polarizability can either be magnitudinal or directional. Hence both the rotational and vibrational motions of the molecule may give rise to Raman effect.

Quantum theory of Raman effect

According to quantum theory, Raman effect involves the interaction of a molecule with a beam of monochromatic radiation of frequency υ_0 and in the process the molecule is excited to quantised upper state.

This interaction leads to three situations.

(i) The molecule might merely deviate the photon $(E = h\upsilon_0)$ without absorbing its energy. This would result in the appearance of the unmodified line in the scattered radiation.

(ii) The molecule, on the other hand, might absorb a part of the energy of the incident photon. This gives rise modified Raman lines called stokes lines whose frequencies would be less than that of the incident radiation.

(iii) Also it may happen that the molecule, itself being in an excited state, imparts some of its intrinsic energy to the incoming photon. This would result in the appearance of antistokes lines whose frequencies are greater than that of the incident radiation.

If the interaction of incident photon and the molecule is imagined as a collision process, the unmodified line is a result of elastic collision and the other Raman lines are due to inelastic collisions. Therefore mechanism of Raman scattering can be analytically expressed by applying the principle of conservation of energy. We can thus write.

$$E_0 + \frac{1}{2}mv^2 + h\upsilon_0 = E' + \frac{1}{2}mv'^2 + h\upsilon'$$

where E_0 and E' are the intrinsic energies and v and v' are the velocities of molecules before and after collision respectively. m is the mass of the molecule, where as υ_0 and υ' are the frequencies of incident and scattered radiation. Since the collision does not, generally, result in any rise in temperature, it may be fairly assumed that the kinetic energy of the molecule remains practically unaltered. In view of this, the above equation becomes

$$E_0 + h\upsilon_0 = E' + h\upsilon'$$

or $$\upsilon' = \upsilon_0 + \frac{(E_0 - E')}{h} = \upsilon_0 + \frac{\Delta E}{h}$$

where $E_0 - E' = \Delta E$

If $E_0 = E'$ (no change in intrinsic energies due to collision process).

$\therefore$ $$\upsilon' = \upsilon_0$$

This represents the unmodified line. If $E_0 < E'$ (inelastic collision resulting in the gain of intrinsic energy of the molecule and a loss of energy of the scattered photon).

$\therefore$ $$E_0 - E' = -\Delta E$$

Thus $$\upsilon' = \upsilon_0 - \frac{\Delta E}{h}$$

This represents the frequencies of stokes lines.

If $E_0 > E'$ (inelastic collision resulting in the loss of intrinsic energy of the molecule) $E_0 - E' = \Delta E$

Thus $$\upsilon' = \upsilon_0 + \frac{\Delta E}{h}$$

This represents the frequencies of antistokes lines.

IMPORTANT FORMULAE

1. Frequency of emission or absorption radiation.

$$\upsilon = \frac{E_2 - E_1}{h}$$

2. Expression for relative population of atoms:

$$N_2 = N_1 e^{\frac{-(E_2 - E_1)}{kT}}$$

3. Rate of absorption transition:

$$R_{abs} = -\frac{dN_1}{dt} = \frac{dN_2}{dt}$$

$$R_{abs} = B_{12} u(\upsilon) N_1$$

4. Rate of spontaneous transition:

$$R_{sp} = -\frac{dN_2}{dt} = \frac{N_2}{\tau_{sp}}$$

$$R_{sp} = A_{21} N_2.$$

5. Rate of stimulated transition:

$$R_{st} = B_{21} u(\upsilon) N_2.$$

6. Relation between Einstein's coefficients

(i) $\frac{A_{21}}{B_{12}} = \frac{8\pi h\upsilon^3}{c^3}$

(ii) $B_{21} = B_{12}$

7. Condition for population inversion

$$N_2 \gg N_1$$

8. Condition for stimulated transition dominate over both spontaneous and absorption radiation

(i) $N_2 > N_1$

(ii) $\frac{B_{21}}{A_1}$ is larger

(iii) $u(\upsilon)$ must be high.

UNIVERSITY MODEL QUESTIONS

Section A

(Answer questions in two or three sentences)

Short answer type questions

1. What is laser? What are its properties?
2. Give three applications of laser.
3. What are Einstein coefficients? Define them.
4. Write down Boltzmann's distribution law for population of energy levels and explain the symbols?
5. What is population inversion? What is the condition to achieve it?
6. What are the conditions to be satisfied to have large stimulated emission?
7. What is meant by pumping? What are the different types of it?
8. Explain what is a metastable state.
9. What is an active medium?
10. What are the essential components of a laser. Explain their functions.
11. In He – Ne laser, lasing is through neon gas. What is then the role of helium?
12. What is the reason for monochromaticity of laser beam.
13. What are the advantages of diode laser?
14. What are the uses of diode lasers?
15. Draw the labelled diagram of a ruby laser.
16. Draw the labelled diagram of a He – Ne laser.
17. Draw the labelled diagram of a diode laser.
18. Draw the labelled diagram of a YAG laser.
19. What is the active centre in a YAG laser? Explain its function.
20. What is Raman effect?
21. What are stokes and antistokes lines?
22. Distinguish between stokes lines and antistokes lines.
23. Distinguish between Raman scattering and Rayleigh scattering.
24. Why stokes lines are more intense than antistokes lines?
25. According to the classical theory what is the prerequisite to the Raman effect.

Section B

(Answer questions in a paragraph of about half a page to one page)

Paragraph / problem

1. Explain the quantum behaviour of light.
2. Explain how does light interact with matter.

3. What is meant by induced absorption? Explain with a two level diagram.
4. What is meant by spontaneous emission? Explain with a two level diagram.
5. How does Einstein predicted stimulated emission of radiation.
6. Explain the stimulated emission of radiation with a two level diagram.
7. Show that $A_{21} = \frac{1}{\tau_{sp}}$ and $A_{12} = 0$.
8. What are the characteriistics of spontaneous emission.
9. What are the characteristics of stimulated emission
10. Spontaneous emission dominates over stimulated emission. Explain.
11. Explain the process of light amplification.
12. Briefly explain optical pumping.
13. Briefly explain electrical pumping.
14. How population inversion is achieved in semiconductor lasers.
15. Explain the function of optical resonator.
16. Briefly explain lasing action.
17. Explain in brief the lasing action of a laser.
18. Describe the working of solid state ruby laser.
19. Describe the working of He – Ne laser.
20. Describe the working of semiconductor laser.
21. Describe the working of YAG laser.
22. Briefly explain the experimental design of Raman effect.
23. Raman lines are symmetrically distributed about the unmodified line. Explain.
24. Explain the unmodified line of Raman spectrum quantum mechanically.
25. Explain the formation of stokes lines on the basis of quantum mechanics.
26. Explain the formation of antistokes lines on the basis of quantum mechanics.
27. Explain the quantum theory of Raman effect.
28. The He – Ne system is capable of lasing at 3.3913μm. Determine the energy difference in eV between the upper and lower levels of this wave length. [0.365 eV]
29. The energy level difference between two laser level is 0.21 eV. Determine the wavelength of radiation. [5.9μm]
30. In a ruby laser, the ruby rod contains a total of 3×10^{19} chromium ions. If laser emits light of 6943Å wavelength, find the energy of one emitted photon and the total energy available per laser. [1.79 eV, 8.6 J]
31. Find the relative atomic population of first excited state and ground state of hydrogen gas at room temperature. $[2.5 \times 10^{-9}]$

32. Find the relative population of the two states in a ruby laser that produces a light beam of wavelength 6943Å at 500 K. [8.7×10^{-19}]
33. The wavelength of emission is 6000Å and the life time τ_{sp} is 10^{-6}s. Determine the coefficient for stimulated emission [$B_{21} = 1.3 \times 10^{19}\,mkg^{-1}$]
34. At what temperature are the rates of spontaneous and stimulated emission equal. Assume $\lambda = 5000Å$. [41,573 K]
35. At what wavelength are the rates of spontaneous and stimulated emission equal at temperature 300K. [69.8μm]

Section C

(Answer questions in about one to two pages)

Long answer type questions-Essays

1. What are Einstein's coefficients? Derive a relation between them.
2. Describe the principle, construction and working of a ruby laser.
3. Explain the principle, construction and working of a He – Ne laser.
4. Explain the principle, construction and working of a semiconductor laser.
5. Explain the principle, construction and working of a YAG laser.
6. Explain the classical theory and quantum theory of Raman effect.

Hints to problems

1 to 30 - see book work

31. $E_2 - E_1 = h\upsilon = \dfrac{hc}{\lambda} = \dfrac{6.6\times10^{-34}\times3\times10^{8}}{3.3913\mu m}\,J$

$$= \frac{6.6\times10^{-34}\times3\times10^{8}}{3.3913\times10^{-6}\times1.6\times10^{-19}} = 0.365\,eV$$

32. $E_2 - E_i = \dfrac{hc}{\lambda}$

$0.21\times1.6\times10^{-19} = \dfrac{6.62\times10^{-34}\times3\times10^{8}}{\lambda}$, Find λ.

33. $E_2 - E_1 = \dfrac{hc}{\lambda} = \dfrac{6.62\times10^{-34}\times3\times10^{8}}{6943\times10^{-10}\times1.6\times10^{-19}}\,eV$

Energy per pulse = Energy of one photon × Total number of atoms.

$$= 1.79\times1.6\times10^{-19}\times3\times10^{19}\,J$$

34. $\dfrac{N_2}{N_1} = e^{\frac{-(E_2-E_1)}{kT}}$

For the hydrogen atom $E_1 = -13.6eV$

and $E_2 = -3.39eV$

$\therefore \quad E_2 - E_1 = 10.21eV$, $k = 1.38 \times 10^{-23} JK^{-1}$

$T = 27^\circ C = 300K$

Calculate $\frac{N_2}{N_1}$

35. $E_2 - E_1 = \frac{hc}{\lambda} = 1.79eV$

$$\frac{N_2}{N_1} = e^{\frac{-(E_2 - E_1)}{kT}}$$

Find $\frac{N_2}{N_1}$ by assuming k

$T = 500K$

36. $B_{21} = \frac{A_{21}\, c^3}{8\pi h\, \upsilon^3} = \frac{A_{21}\, \lambda^3}{8\pi h}$

where $A_{21} = \frac{1}{\tau_{sp}} = 10^6$

37. $B_{21}\, u(\upsilon) = A_{21}$

i.e., $\frac{1}{e^{\frac{h\upsilon}{kT}} - 1} = 1$

$\upsilon = \frac{c}{\lambda} = \frac{3 \times 10^8}{5 \times 10^{-7}} = 6 \times 10^{14}$ $T = ?$

Assuming h and k, find T

38. When stimulated and spontaneous emission are equal, we have

$$\frac{1}{e^{\frac{h\upsilon}{kT}} - 1} = 1$$

Putting the values of h, k and T, find υ.

Then use $\lambda = \frac{c}{\upsilon}$.